Numerical Modeling of Transient Behavior in Far-Infrared Photoconductors

Nancy M. Haegel
Department of Physics, Fairfield University, Fairfield, CT 06430

ABSTRACT

Results from numerical simulation of Ge:Ga photoconductors will illustrate progress in understanding some of the more problematic features of the transient behavior, including the hook effect and the response to complex modulated inputs. A simulated hook response that closely resembles experimental behavior is observed for conditions of reduced optical generation near the injecting contact. Modification of contact design may allow production of detectors in which the initial component of the transient represents the full incident flux.

INTRODUCTION

The complex transient response of extrinsic photoconductors to variations in incident photon flux has been a limiting factor for low background performance since first identified by Williams in 1964[1]. Extensive analytical work has been performed to understand the transient behavior and to aid in the calibration of detector output[2-4]. The basic physics of the phenomenon is well understood: excess carriers, generated in response to an increase in photon illumination, can either drift or diffuse to a contact region, where they recombine. This limits the initial gain of the device. Since changes in injection require local changes in the space-charge-governed electric field in the region adjacent to the contact, the charge that is lost to the contact cannot be immediately replaced in the bulk by increased injection. The result is a slow component of the response whose magnitude corresponds to the amount of sweep-out and/or out-diffusion and whose time constant depends on the rate of readjustment of internal fields.

A finite difference model has been developed to study the transient behavior by solving the continuity equation, Poisson's equation and the detailed balance equations simultaneously in one dimension for majority carriers. It allows for simulation of the transient response including drift, diffusion and displacement currents in all regions of the device and has been previously described in detail [5-7]. The model calculates total current as a function of time, based on spatial and temporal variations of electric field and carrier distribution within the device. Required inputs include the doping levels (and any spatial variations) and material parameters of mobility and capture cross section, as well as basic operating parameters of bias, temperature and flux variation. There are no empirical or fitting parameters.

The model includes, as stated, all current components, including the diffusion currents that play key roles in the near contact regions. Both contacts are included, treated as heavily doped p^+ (for Ge:Ga) regions with temperature independent concentrations of free carriers. No assumptions are made about the electric field distribution, since the boundary conditions are simply the terminating free hole concentrations in each contact and the total voltage drop across the device. The key assumptions that are made are constant mobility and recombination cross section (i.e., no field dependence to the material parameters). These are reasonably good approximations for the low fields of interest for very far IR photoconductors.

Analytical models for the transient response have been most successful in describing the behavior of extrinsic Si photoconductors, which operate under higher electric fields[8]. The numerical model has been developed for and applied primarily to the transient response of Ge:Ga detectors, usually operated at electric fields of ~ 0.5 – 1.0 V/cm. It provides the flexibility to incorporate spatial variations of illumination and doping as a function of distance between the contacts. In recent work, this capability has been used to provide new insight into the hook response, often a characteristic of Ge:Ga photoconductors under low background illumination, and to suggest new approaches to contact fabrication that could improve device performance by modifying the transient behavior.

Contact information for N. Haegel: Email: nhaegel@fair1.fairfield.edu

UNIFORM ILLUMINATION RESULTS

Under uniform illumination, the simulations, at least in the small signal limit, are consistent with analytical modeling. The fast to slow component ratio is dependent on the gain and the characteristic transient time is dependent on the background flux ($\tau \sim 1/g$) and signal size. Simulation predicts, and experiments confirm, that the initial fast fraction of the signal is a constant, independent of background and/or signal size, for a single step when starting from steady state. However, when the transient response for several signals overlaps, i.e., when new signals are incident during the transient following a background flux change, one sees a variation in the magnitude of the initial signal (fast fraction). This type of behavior can be probed through simulations like that shown in Figure 1, where short duration signals are periodically imposed in a sequence where the background flux is first increased and then returned to its original value.

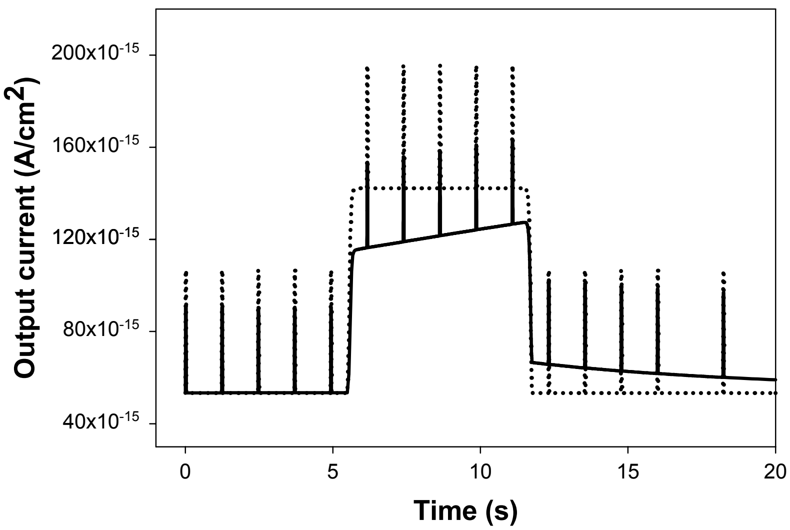


Figure 1: Comparison of flux generation rate (dashed) to output current (solid) for Ge:Ga detector under uniform illumination. T = 3.0 K with applied bias of 50 mV for a 0.5 mm intercontact distance (1 V/cm). Pulse signals and background change both have magnitude $\Delta g = g$ where $g = 2.2 \times 10^7\ cm^{-3}s^{-1}$. Simulations at higher/lower flux levels would move the transient to shorter/longer time scales.

HOOK RESPONSE

Although some non-monotonic and oscillatory transient behavior is predicted, both analytical and numerical modeling using uniform illumination fail to successfully replicate the distinctive nature of the hook effect for many operating conditions for Ge:Ga photoconductors. The hook response is a response to an increase in optical signal in which the initial current increase (a fast process usually determined by the time constant for changing the incident light) is followed by a decrease in current prior to the growth to the final steady state value. The hook response is most apparent for cases of higher applied bias, larger relative signals and lower background flux. It is not observed as readily in stressed detectors, even when made from the same material and with similar contacts.

In comparing simulation results to experimental transients for the Ge:Ga photoconductors on MIPS, it was determined that the transient time was significantly longer than that expected for the incident flux levels. One possible explanation was the non-uniform illumination associated with the optical concentrators used to direct light into the devices[9]. Simulations were performed in which the optical generation rate was varied as a function of the intercontact distance, with the illumination reduced to 15% of the bulk level in a region adjacent to the injecting contact. Two significant changes occurred in the transient response as a result. The first was a several order of magnitude increase in slow component characteristic time, consistent with experimental observations in the MIPS array. The second was the appearance of a feature that reproduced all the characteristics of the hook response[7].

The physics of the behavior can be understood by studying three-dimensional plots of electric field and carrier concentration as a function of time and position between the contacts[7]. These show that a less highly illuminated region near the injecting contact causes a local field overshoot during the transient response that results in a field decrease in the remainder of the device. This field variation, coupled with the carrier distribution, results in the transient decrease in net current. These simulations have demonstrated that the hook response is caused by a decrease in current during the slow component of the response, rather than any additional current associated with the initial fast component.

Most Ge:Ga photoconductors demonstrate some hook effect at a sufficient combination of low temperature, higher field and larger signal, even without the type of optical concentrator responsible for the non-uniform illumination in the MIPS detectors. We believe that the nature of the standard contact (implanted p^+ layer covered with metallization), in combination with transverse illumination, causes some optical shadowing in the near contact region. Simulations have shown that we can produce the hook effect for non-uniformly illuminated regions as low as 25 to 50 μm.

To test this idea experimentally, Ge:Ga detectors from the ***same bulk material and with the same contact technology*** were fabricated to allow for both standard transverse illumination and illumination through a front transparent contact. In the latter case, the illumination in the near contact region would be comparable to or higher than the illumination level in the remainder of the bulk, eliminating any high resistivity region associated with lower optical generation. Comparison of the two results, for equal operating temperature, applied bias and signal size, is shown in Figures 2 and 3.

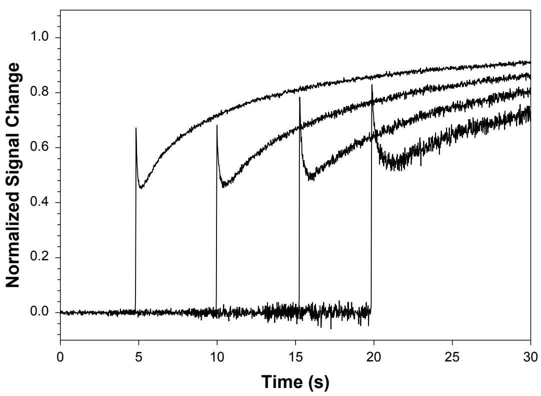


Figure 2: Transient response for Ge:Ga detector with standard transverse contact geometry. T = 3.0 K and applied field = 1 V/cm. Results are normalized for comparison, but represent a range of signal sizes from 10 to 50 mV

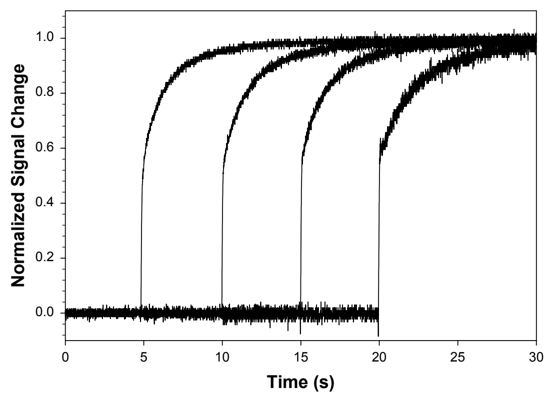


Figure 3: Transient response for Ge:Ga detector with illumination through a transparent contact. T = 3.0 K and applied field = 1 V/cm. Results are normalized for comparison, but represent a range of signal sizes from 20 to 70 mV.

Subsequent studies have shown that some hook like behavior can still be observed with transparent contacts at higher fields and lower background fluxes, though comparisons under similar conditions continue to show significant reduction in hook effect when comparing transverse to transparent illumination. This behavior is believed to be associated with a residual high resistivity region associated with enhanced compensation in the tail of the implanted contact region (See Contact Modification below).

Incorporating the hook behavior into the model has provided new insights into the interpretation of experimental transient data, particularly as a function of signal size. Figure 4 shows simulated transient response to a single flux increase for a Ge:Ga detector, under non-uniform illumination, as a function of increasing signal size on fixed background. Results are presented on both linear and logarithmic time scales. One sees that the degree of hook behavior increases with increasing signal size, but also that the time constant for the onset of the hook behavior is reduced. The linear plot shows that the fast fraction remains constant as a function of signal size for these isolated steps. However, the "turn-on" time required to acquire the full fast component response will also vary with signal size. When this is not the case experimentally (e.g., when using thermal emission devices to produce calibrating signals, where the turn on time may actually increase for increasing signal size), the varying time constant of the hook response can affect the apparent fast fraction. This trend has been observed in studies of the hook response as a function of signal size in individual pixels[10].

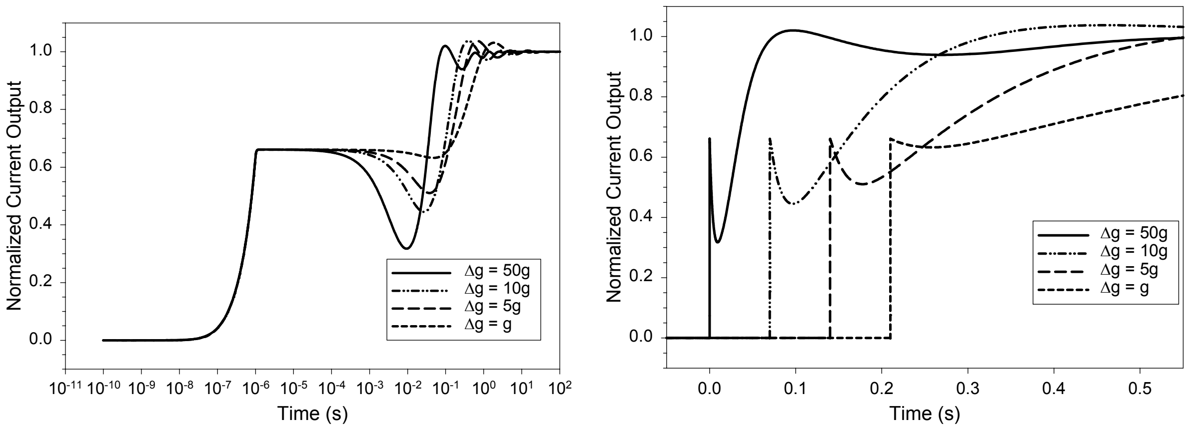
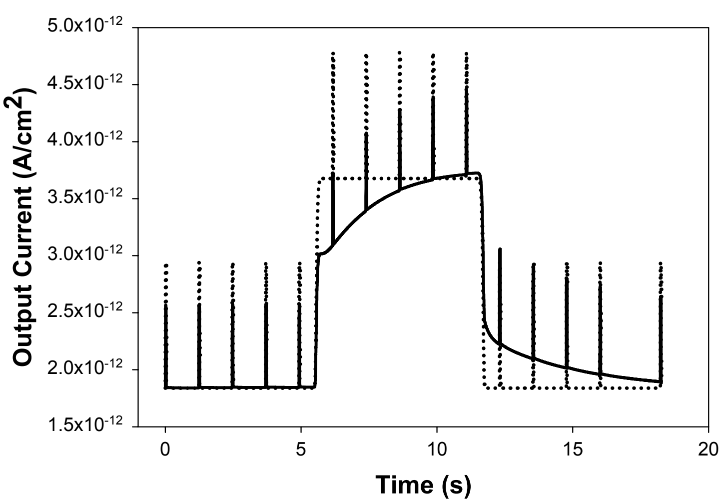


Figure 4: Simulated transient response, under non-uniform illumination conditions, as a function of signal size on fixed background. Hook effect is present in all cases, with the magnitude and time constant of the hook varying with signal size Δg.. All simulations are for Ge:Ga at 3.0 K with an applied field of 1.0 V/cm. Response is shown on both a logarithmic (left) and linear (right) time scale.

MODULATED RESPONSE IN THE PRESENCE OF THE HOOK EFFECT

Figure 5 shows the response, with a hook behavior, for an input signal series similar to that in Figure 1. The time constant associated with the transient behavior is increased and the hook response is apparent, not only in the initial transient decrease for an individual signal, but also in the collective response to multiple modulations. Although not illustrated, a series of short signal pulses on a fixed background replicates, over time, the hook response of a single step. This is consistent with experimental results. Unlike the response under uniform illumination in Figure 1, the series of signal pulses in Figure 5 show an obvious trend of decreasing in magnitude after the background increase and then increasing after the background is returned to its initial value. This indicates that the variation in fast fraction in the presence of the hook behavior reflects complex changes in the near-contact field, rather than solely the changes in the background current.

Figure 5: Comparison of flux generation rate (dashed) to output current (solid) for Ge:Ga detector with hook response. $T = 3.0$ K with applied bias of 50 mV for a 0.5 mm intercontact distance (1 V/cm). Pulse signals and background change both have magnitude $\Delta g = g$ where $g = 2.2 \times 10^9$ $cm^{-3}s^{-1}$. Simulations at higher/low flux levels would move the transient to shorter/longer time scales.



Finally, we present in Figure 6 an example of a complex modulation series done to assist in the understanding of the expected transient response for the Ge:Ga detectors from the MIPS 70 μm array for SIRTF. The input photon signal was designed to simulate "stim flashes" for calibration with 3 signal integrations following. The results illustrate many of the experimentally observed features, including latent transient behavior following the stims and variations in effective responsivity after changes in background flux. Preliminary analysis of this data indicates that the signals, when calibrated by the variations in stim response, can be corrected to approximately 5%, except in the period immediately following a background change. The modeling can be used to optimize the timing and relative magnitudes for the calibration sequence and also to investigate limiting cases that may be difficult to test experimentally.

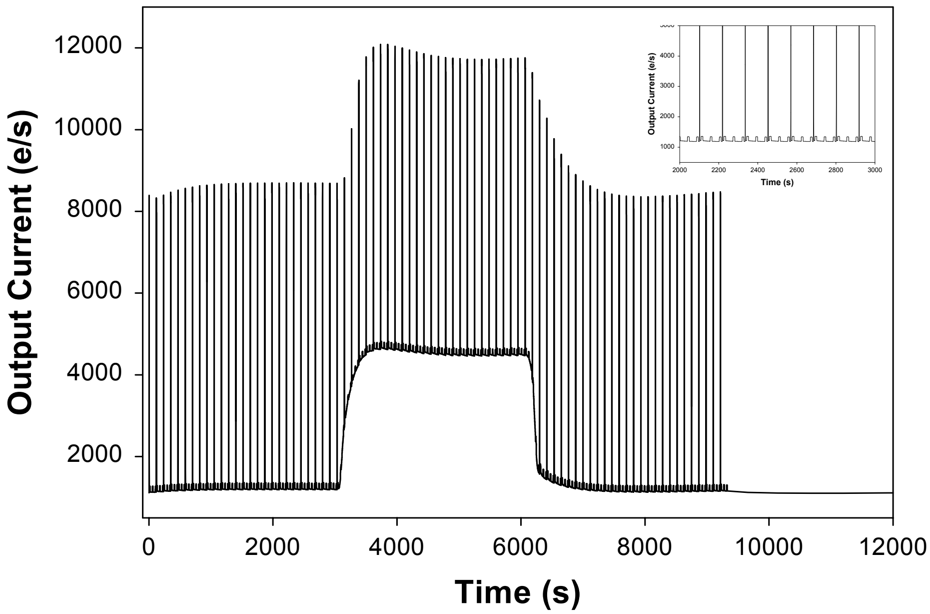


Figure 6: Transient simulation for a series of signals between constant calibration signals. One sees the effect of the underlying background variation. Expanded inset in the upper right shows the interspersed signals. Simulation was performed for a Ge:Ga detector with a hook response. Background generation rate was ~ 10^7 $cm^{-3}s^{-1}$.

POTENTIAL FOR CONTACT MODIFICATION

The hook response modeling illustrates the importance of the near-contact region in determining both the nature and the time constant of the transient response. The challenge of determining the exact doping profile, for both majority and minority (compensating) dopant, is met in the analytical modeling by the introduction of a fitting parameter that characterizes contact behavior. In the numerical modeling, it is possible to create dopant profiles for both dopant types. Detailed comparison of simulated to experimental transient data, particularly for the case of uniform through-contact illumination, could be used to develop appropriate doping profiles for boron implantation into Ge:Ga detectors.

However, recognizing that modification of the field profile associated with the contact could also be used to affect the sweep-out behavior, we have performed simulations in which an extended counterdoping profile was introduced into the near-contact region. Minority dopants (n type for the case of Ge:Ga) could be implanted at higher energy than the majority contact dopant. The maximum minority dopant level, however, would be kept below the bulk majority doping to avoid the creation of any p/n junctions, i.e., any regions that would become net n type in the p-type device. In the simulation, we have graded the compensating dopant with a truncated exponential function, extending approximately 25 μm into the bulk.

Figure 7 shows the simulated transient including this contact modification, compared to the transient result for the same flux change with a standard contact model. One sees that the introduction of the extended, more highly compensated region causes an increase in the initial fast fraction and a significant time extension in the hook like response. The initial fast fraction is almost one, with a current decrease following at a delayed time. This transient fluctuation has been found to scale inversely in time with the incident flux, meaning that, for low background applications, it may be possible to monitor the full signal in a fast time regime prior to transient variations. In effect, this contact modification may offer the option to create a detector whose initial fast component represents the full signal.

A priority for future work should be the full exploration of the parameter space for possible contact modifications, followed by fabrication and testing of prototype devices. New contact design, combined with the use of transparent contact geometry, may create significant changes in the transient response. An effective elimination of the fast/slow component response, with an initial signal that represented the actual incident flux, would be a major performance enhancement for next-generation far IR photoconductors.

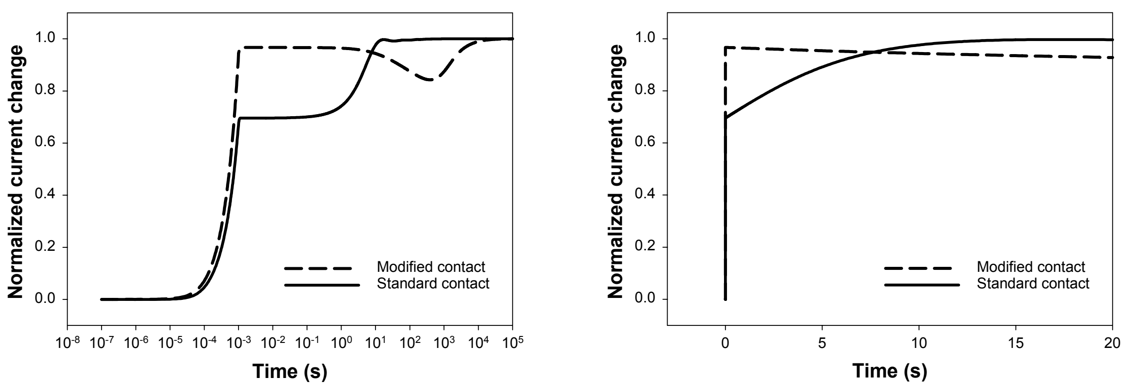


Figure 7: Comparison of transient response with standard contact and modified contact. Creating a high resistivity layer near the injecting contact produces an increase in fast fraction and a delay in the onset of the slow component decrease. Simulations were performed for uniform illumination, T = 3.0 K and an applied field of 1.0 V/cm. Results are normalized from 0 to 1 and presented on both a logarithmic (left) and linear (right) time scale.

ACKNOWLEDGEMENTS

The author is grateful to A. M. White, J. W. Beeman and G. Rieke for long term collaboration. Many students at Fairfield University have contributed to this work, most recently M. Smylie, W. R. Schwartz and C. Pullen. We acknowledge the support of NASA Grant NAG5-8650 from the Office of Space Science.

REFERENCES

1. R. L. Williams, J. Appl. Phys. **40**, 184 (1969).
2. L. A. Vinokurov, B. I. Fuks, Sov. Phys. Semicond. **25**, 11 (1991).
3. B. I. Fouks, Proc. Photon Detectors for Space Instr. ESA **SP-356**, 167 (1993).
4. B. I. Fouks, J. Schubert, SPIE **2475**, 487 (1995).
5. N. M. Haegel, C. R. Brennan and A. M. White, J. Appl. Phys. **80**, 1510 (1996).
6. N. M. Haegel, J. C. Simoes, A. M. White and J. W. Beeman, Appl. Opt. **38**, 1910 (1999).
7. N. M. Haegel, W. R. Schwartz, J. Zinter, A. M. White and J. W. Beeman, Appl. Opt. **40**, 5748 (2001).
8. A. Coulais, A. Abergel, "Transient Effects of IR Photodetectors: The Lessons from ISO," Paper **3-13**, Proc. Far-IR, Sub-mm and mm Detector Technology Workshop, Monterey, CA, 2002.
9. See http://sirtf.caltech.edu for instrument overviews
10. N. M. Haegel, C. Pullen, W. R. Schwartz, M. P. Smylie and J. Zinter, Proc. 21st Intl. Conf. on IR and Millimeter Waves, Sept. 2001, Toulouse, France.